Skill Learning: Putting Procedural Consolidation in Context

Dispatch

Edwin M. Robertson

Information acquired during skill learning continues to be processed long after practice has ceased. An important aspect of this processing is thought to be the transformation of a memory from a fragile to a stable state: a concept challenged by a recent study.

Memories pass through multiple stages in their development, the most recognised of which are encoding, consolidation and retrieval [1]. Each stage is associated with an array of important neural processes; for example, during consolidation, memories can be enhanced and/or stabilised [2–4]. The notion that memories are initially encoded in a fragile state and, over time, are transformed into stable memories has been influential; it provides an explanation for key features of the amnesiac syndrome, and has motivated important experimental work [5]. Given the contribution that this idea has made to our understanding of declarative memory — memory for facts and events — it is not surprising that evidence has been sought that other types of memory also undergo stabilisation. This would provide a common principle: all types of memory, regardless of the neural system they engage, would initially be encoded in a fragile state and later transformed into stable memories.

Pioneering experiments, eight years ago, supported this idea, showing that, like declarative memory, procedural memory — memory for skills — also requires stabilisation following encoding. These studies showed that a newly acquired skill (task A) can be lost if an individual immediately attempts to acquire skill in another, similar task (task B). If time passes between acquisition of the first skill and training in the second, however, the amount of interference decreases (Figure 1A) [6]. This additional time perhaps gives an opportunity for the neural processes of consolidation to transform a fragile procedural memory into a stable memory. Once the memory for the first skill is stabilised, the limited resources to maintain a fragile memory become available once again, allowing a second skill to be acquired without disrupting the first.

In these studies, participants made reaching movements towards targets arranged in a circle around a central starting location. A participant's initial reaching movements were pushed off course by a force field, so that the initial trajectories were curved. With practice, participants learnt to adapt to the force field, and produced straight reaching movements. The properties of the force field differed in each task. For example, in task A the force field might have pushed reaching movements in an anticlockwise direction, whereas in task B, it might have pushed them in a clockwise direction. Participants only retained the ability to compensate for the force-field when they were exposed to the force-field of task B at least 6 hours after their initial exposure to task A. A similar pattern of observations were made in later studies [7,8]. This consensus however, has not gone unchallenged.

The principle that a procedural memory is stabilised following skill acquisition has been questioned in two recent studies [9,10]. Both studies showed interference between two tasks, A and B. Performance in task B impaired participants' performance on task A at re-testing ('proactive interference'). Retroactive interference, in which exposure to task B disrupts the retention of skill for task A, was thought to be minimal. Critically, in both studies the interference between the tasks was constant, despite increasing the interval between them. This finding fails to support the notion that procedural memories change from a fragile to a stable state. Such a time-dependent transformation should lead to a decrease in the susceptibility of a skill memory to disruption. This would be observed as a decrease in the interference between tasks as the interval between them is lengthened. But the interference between tasks was constant, suggesting that procedural memories are not stabilised. This could be either because these memories do not require stabilisation, or because they never achieve a protected state and remain vulnerable to interference. A recent study provides evidence favouring this latter possibility [11].

Confirming earlier work, this recent study [11] showed that the interference between tasks is unaffected by the interval between being exposed to distinct force fields — that is, between task A and task B. But the new results challenge the notion that the interference had exclusively a proactive source. In the absence of a force-field, participants performed reaching movements before being re-tested on task A. These 'washout' trials minimised the possible proactive interference from recent exposure to task B. Nonetheless, interference between the tasks could still be detected, implying that the interference had a retroactive source. This suggests that acquiring skill in task B disrupted the memory trace of task A.

Furthermore, the skill in task A remained susceptible to interference from task B even when the interval between these two tasks was as long as 24 hours (Figure 1B). This implies that a procedural memory may never become fully stable and instead remains vulnerable to interference. When exposed to task B, participants may have retrieved the procedural memory associated with task A and modified it, 'overwriting' the

Center for Non-invasive Brain Stimulation, Harvard Medical School, Beth Israel Deaconess Medical Center, 330 Brookline Avenue, Kirstein Building KS 454, Boston, Massachusetts 02215, USA. E-mail: emrobert@bidmc.harvard.edu

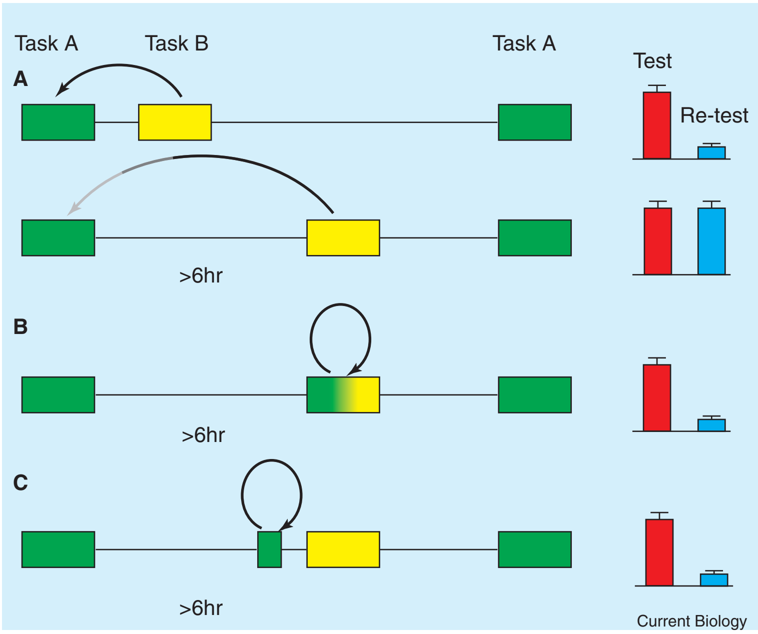

Figure 1. Sources of interference in procedural learning, and the possible role of context.

(A) Learning two tasks in quick succession can cause the skill expressed at re-testing to be less than that at testing. This interference may be because a second task (task B) impairs retrieval of skill A (proactive interference, not shown); alternatively, exposure to task B may disrupt the retention of skill A (retroactive interference, shown). The disruptive influence of task B is lessened as the time between task A and B is lengthened (shown as a fading arrow) [6], perhaps because with time the memory trace of skill A is transformed from a fragile into a stable state. This makes the skill memory for task A less susceptible to disruptive retroactive interference from task B. (B) Several recent studies have found that the interval between exposure to task A and task B has little affect upon the magnitude of interference [9–11]. This questions the need for memories to be stabilised, and instead suggests that the interference between tasks has a proactive source. But even when 'washout' trials remove the affects of earlier learning, interference remained suggesting that it is unlikely to have a proactive source [11]. Hence, without evidence for either proactive or retroactive interference, it may be that exposure to task B causes the memory trace of skill A to become unstable and susceptible to interference. Yet, this explanation is incomplete, because it suggests that individuals can never acquire more than a single skill. This paradox may be resolved if participants believed they were retrieving task A, when actually being exposed to task B: retrieving task A would cause the memory for this task to become unstable and susceptible to interference from task B. (C) When a contextual cue signals the switch from task A to task B, interference only arises when task A is retrieved moments before task B [17]. In contrast, when task A and task B are separated by many hours there is little interference. Thus a participant's awareness of whether they are retrieving an old skill or learning a new skill may determine the stability of the old memory.

memory for task A with information relevant to task B. This explanation gives a useful interpretation of the study's observations, but it contains a paradox. It implies that learning a new skill leads to the automatic destruction of another skill. It would never be possible to have skill in more than one task! Our ability to acquire multiple skills may depend upon having contextual cues available to signal the switch from one task to another.

Learning to produce skilful reaching movements in several different force fields is possible when participants are given contextual cues — such as a different screen colour — when the force fields are changed [12]. Participants can also express different degrees of proficiency at producing the same sequence of finger movements in different contexts [13]. The context, and whether a sequence of finger movements is acquired intentionally or unintentionally, can also modify the processes engaged following skill acquisition [14]. Whether a procedural memory becomes unstable at retrieval — a phenomenon referred to as re-consolidation (see [15,16] for reviews) — may also depend upon the availability of contextual cues. When exposed to task B, participants may be retrieving the procedural memory for task A [11].

Such inappropriate retrieval of a skill might have occurred because participants had no way of knowing that the task had changed: there was no cue signalling the switch from task A to task B. Later, at re-testing, participants failed to show any skill at task A. In contrast, when contextual cues are provided, there is no confusion between tasks; consequently, the memory associated with a procedural task only becomes labile again when that specific task is retrieved, not when participants attempt to acquire any new skill (Figure 1C) [17]. Contextual cues may prevent the inappropriate retrieval of a skill, protecting it from becoming unstable when one attempts to learn a new skill; however, this may not always be the case [10]. Other factors, for example, the type of practice and the type of skill acquired, may affect whether a procedural memory requires stabilisation [3,9,18].

Contextual cues seem likely to make an important, but as yet under-explored, contribution to skill learning. Borrowing the concepts of consolidation and re-consolidation from other areas of memory research has helped deepen our understanding of procedural learning — an appreciation of the importance of context may do likewise.

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